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Current driven magnetic permeability interference sensor using NiFe/Cu composite wire with a signal pick-up LC circuit

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A novel micro magnetic sensor called the Current Driven Magnetic Permeability Interference (CDMPI) sensor has been developed and the key parameters of the sensor have been studied. The sensor consists of a sensing element in a form of composite wire of a 20 μm copper core electrodeposited with a thin layer of soft magnetic material ($Ni_{80}Fe_{20}$), an ac power source driving the permeability of the magnetic coating layer of the sensing element into a dynamic state, and a signal pickup LC circuit formed by a pickup coil and an capacitor. Experimental studies on the CDMPI sensor have been carried out to investigate the key parameteres in relation to the sensor sensitivity and resolution. The results showed that for high sensitivity and resolution, the frequency and magnitude of the ac driving current through the sensing element each has an optimum value, the resonance frequency of the signal pickup LC circuit should be equal to or twice as the driving frequency on the sensing element, and the anisotropy of the magnetic coating layer of the sensing wire element should be longitudinal.

1 Introduction Magnetic field sensing technology has been driven by the need for improved sensitivity, smaller size, and improved compatibility with electronic systems. There are various magnetic field sensors such as Hall devices, fluxgate devices, magnetoresistors and Superconducting Quantum Interference Device (SQUID). So far only the SQUID is capable of detecting the magnetic field of the brain. The cost of SQUID is extremely high, at about US$ 3 million. Recently, sensors based on the Magnetic Permeability Interference (MPI) have shown potential in the development of very weak field measurements. For example, the commercially available fluxgate and magnetoimpedance sensors are able to detect magnetic field of 10^{-10} T or even higher resolution [1, 2].

In this study, a novel micro magnetic sensor called the Current Driven Magnetic Permeability Interference (CDMPI) sensor has been developed and the experimental parameters of its components have been investigated. The sensor has a sensing element which is a composite wire formed by a 20 μm copper core electrodeposited with a thin layer of soft magnetic material ($Ni_{80}Fe_{20}$), an ac power source driving the sensing element with a high frequency current, and a signal pickup circuit consisting of a signal pickup coil together with a LC output circuit. Experimental studies on the CDMPI sensor have been carried out to study the key parameters governing the sensitivity and resolution of the sensor. The parameters include the magnetic anisotropy of the sensing element, the magnitude and frequency of the ac driving current, and the LC resonance frequency of the signal pickup circuit.

2 Sensor design The sensor comprises three parts: a sensing element, an ac power source and a signal pickup circuit, as shown in Fig. 1. The sensing element contains extremely soft ferromagnetic magnetic materials such as Co-based amorphous, Fe-based nanocrystalline alloy, permalloy [3–5]. In the present

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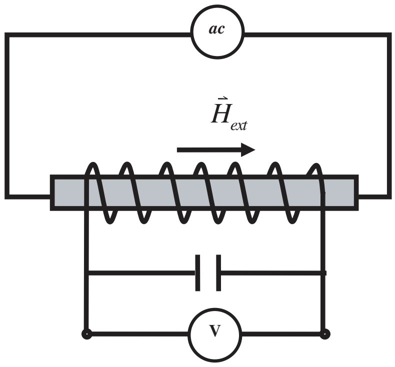

Fig. 1 (online colour at: www.interscience.wiley.com) CDMPI sensor, comprising a sensing element, an ac power soruce having a high frequency current passing throuhg the sensing element, and a signal pickup LC circuit.

study, a composite wire formed by a 20 µm copper core electroplated with a layer of $Ni_{80}Fe_{20}$ was used. The ac power source supplies a high frequency current passing through the sensing element. The signal pickup circuit is formed by a signal pickup coil and a capacitor.

The sensor works based on the permeability of the soft ferromagnetic material in the sensing element, which is driven into a dynamic state by the high frequency current through it. The permeability of the sensing element at a dynamic state is extremely sensitive to external magnetic field and varies with it. The variation of the permeability in variation with the external field changes the longitudinal magnetic flux in the sensing element. The change of longitudinal magnetic flux induces a signal in the pickup coil. The signal is enhanced by the LC resonance circuit. Therefore, the sensitivity and resolution of the sensor depends on three key parameters: 1) the magnetic anisotropy of the sensing element, 2) the magnitude and frequency of the ac driving current, and 3) the LC resonance frequency of the signal pickup circuit. The details are shown in the next section.

3 Sensor Parameters

3.1 Anisotropy of the sensing element The anisotropy structure of the sensing element may be varied during the sensing element development [6]. The influence of the anisotropy on the sensitivity and resolution of the sensor was tested. The experiments on the sensing elements with circumferential and longitudinal anisotropy were carried out using the same testing conditions. The two samples had almost the same maximum magneto-imedance, MI, frequency and maximum MI ratios. Tab. 1 shows a comparison of the sensitivity and resolution of the sensor with different anisotropic sensing elements. The dependence of the output against the external magnetic field is shown in Fig. 2.

It can be seen from the Tab. 1 and Fig. 2 that the sensing element of longitudinal anisotropy has higher sensitivity and resolution than circumferential one. Using such an anisotropy structure sensing element, a maximum sensitivity of 2273.7 mV/Oe and a maximum resolution of 7.0×10^{-9} T was achieved for the external field ranging from 0 Oe to 0.7 Oe.

3.2 Magnitude and frequency of the ac driving current The circumferential magnetic field induced by the driving current will magnetize the sensing element to partially or fully saturated state. For different soft ferromagnetic materials, there is an optimum working frequency, at which the permeability of the magnetic material materials can be driven into a most dynamic state. The extent of the magnetization may affect the sensitivity of the CDMPI sensor. For each sensing element, there is an optimum frequency, $f_{MI,}$ at which the magneto-impedance of the sensing element reaches the maximum. In order to

Table 1 Sensor sensitivity and resolution for sensing elements of different anisotropy.

anisotropy	sensitivity (mV/Oe)	resolution (T)
circumferential	1165.6	8.3×10^{-8}
longitudinal	1270.8	6.2×10^{-8}

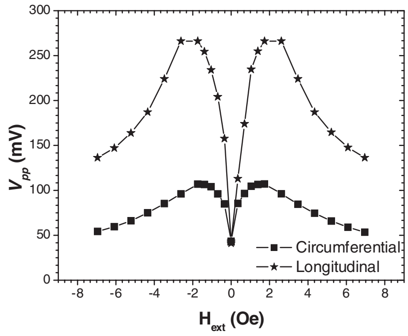

Fig. 2 Dependence of the sensor output on the anisotropy of sensing element.

study the effect of the magnitude of the driving current on the sensitivity of the sensor, experiments are conducted at the frequency condition of driving current frequency $f_{DR} = f_{MI}$. The sensitivity of the sensor is obtained by calculating the gradient of the output voltage against the external magnetic field, H_{ext}. The effect of the magnitude of the input voltage, V_I on the sensitivity of the sensor is shown in Fig. 3. It can be seen that the output voltage signal from the sensor not only contains the 1st harmonics of the driving frequency but also higher order harmonics. Further, as V_I was increased, the dominant output voltage signal changes from first harmonics to second harmonics and then to higher order harmonics. The maximum sensitivity for the sensor was attained at V_I = 1400 mV, which was in the second harmonic region. This clearly indicates that the sensor is most sensitive when the output voltage signal is at the second harmonic region.

The effect of the driving frequency, $f_{DR,}$ on the sensor sensitivity was also investigated. The results are shown in Fig. 3. It can be seen that the curve displays a maximum sensitivity occurring at the condition whereby $f_{DR} = f_{MI,}$ (f_{MI} = 10 MHz) at which the sensing element can be driven to the most dynamic state.

The optimum frequency of the driving current is closely related to the properties of the sensing element, and can be determined by obtaining the magneto-impedance of the sensing element when an ac current of a range of driving frequencies was passing through it. The magnitude of the optimum driving current is also closely related to the properties of the sensing element, and the optimum value is determined such that the circumferential magnetic field of the sensing element reaches a saturation level.

3.3 LC resonance frequency To study the effect of LC resonance frequency, f_{LC}, on the sensitivity of the sensor, the capacitance value and the inductance of the pickup coil may be varied to adjust f_{LC}. Experiments were carried out using a pickup coil of 100 turns initially and the driving frequency, f_{DR}, and magnitude of input voltage were also kept constant at 10.0 MHz and 6.4 V, respectively. When the critical frequency met the condition $f_{LC} = f_{DR}$ or $f_{LC} = 2f_{DR}$, the output peak-to-peak voltage, V_{pp} was obtained as the maximum variation against the external magnetic field. The result also showed that when a larger capacitance value of the capacitor is used, both the sensitivity and resolution of the sensor deterio-

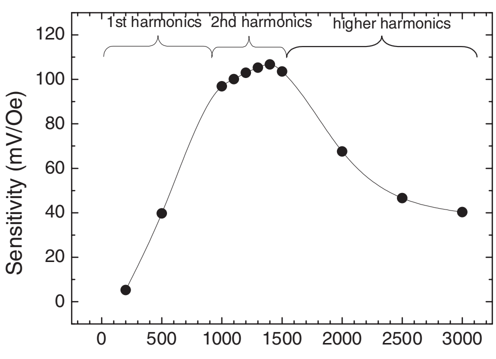

Fig. 3 Sensor sensitivity varying against magnitude of the driving voltage on sensing element.

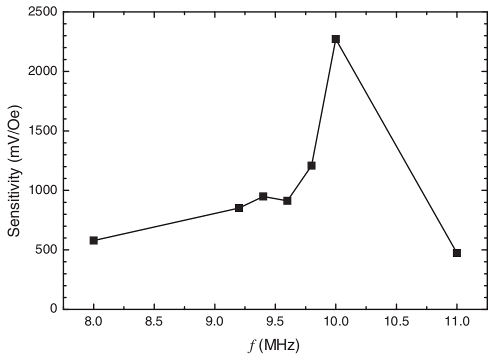

Fig. 4 Sensor sensitivity varying against frequency of the driving current.

rates. When the CDMPI sensor was operated at the critical frequency condition whereby the resonance frequency was of the same magnitude as or double that of the driving frequency, it was found that the sensor had the highest sensitivity and resolution. This is due to the occurrence of the magnetic resonance when the driving frequency of the sensing element, f_{DR}, coincides with the resonance frequency of the LC circuit, f_{LC}. The effect of the occurrence of this resonance is that it will cause the output peak-to-peak voltage, V_{pp} to be amplified numerous times and these results in the highest sensitivity of the sensor at this critical condition. This is very critical in the CDMPI sensor as higher sensitivity of the sensor will result in more precise measurements and higher resolution of the sensor will mean that the sensor will be able to detect weaker magnetic fields.

The value of the capacitor should be determined such that the resonance frequency of the signal pickup circuit is equivalent to the optimum frequency of the driving current, or is twice the magnitude of the optimum frequency of the current driving the sensing element. The sensor output is the voltage induced in the pickup coil when there is a variation in the magnetic field.

4 Conclusions A Current Driven Magnetic Permeability Interference (CDMPI) sensor has been developed. The sensor comprises a sensing element, an ac power source having a high frequency current passing through the sensing element, and a signal pickup LC circuit. The effects of the sensor parameters on sensor sensitivity and resolution have been investigated. The results showed that for high sensitivity and resolution, the frequency and magnitude of the ac driving current through the sensing element each has an optimum value, the resonance frequency of the signal pickup LC circuit should be equal to or twice as the driving frequency on the sensing element, and the anisotropy of the magnetic coating layer of the sensing wire element should be longitudinal. Using a composite wire of 20 µm copper core electrodeposited with a thin layer of soft magnetic material ($Ni_{80}Fe_{20}$) as the sensing element for the sensor, a maximum sensitivity of 2273.7 mV/Oe and a maximum resolution of 7.0×10^{-9} T was achieved at the magnetic field ranging from 0 Oe to 0.7 Oe.

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